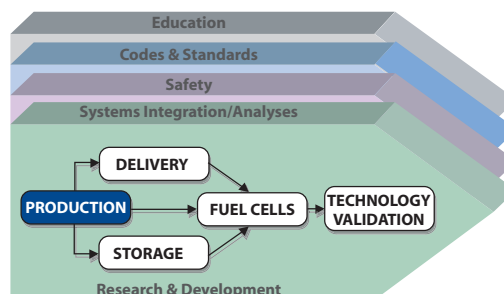


## 3.1 Hydrogen Production

Hydrogen can be produced from a variety of feedstocks using a variety of process technologies. Feedstock options include fossil resources such as coal, natural gas, and petroleum, and renewable resources such as biomass, sunlight and wind. Process technologies include thermochemical, biological, electrolytic and photolytic.



### 3.1.1 Technical Goal and Objectives

#### Goal

Research and develop low-cost, highly efficient hydrogen production technologies from diverse, domestic sources, including fossil, nuclear, and renewable sources.

#### Objectives

- By 2010, reduce the cost of distributed production of hydrogen from natural gas and/or liquid fuels to \$1.50/kg (delivered, untaxed) at the pump (without carbon sequestration).
- By 2010, develop and demonstrate technology to supply purified hydrogen (purity sufficient for polymer electrolyte membrane (PEM) fuel cells) from biomass at \$2.60/kg at the plant gate (projected to a commercial scale 75,000 kg/day).<sup>1</sup> The objective is to be competitive with gasoline by 2015.
- Develop advanced renewable photolytic hydrogen generation technologies. By 2015, demonstrate an engineering-scale biological system that produces hydrogen at a plant-gate cost of \$10/kg projected to commercial scale. By 2015, demonstrate direct photoelectrochemical water splitting with a plant-gate hydrogen production cost of \$5/kg projected to commercial scale. The long-term objective for these production routes is to be competitive with gasoline.
- By 2010, verify renewable integrated hydrogen production with water electrolysis at a hydrogen cost of \$2.50/kg (electrolyzer capital cost of \$300/kWe for 250 kg/day at 5,000 psi with 73% system efficiency). By 2010, verify large-scale central electrolysis at \$2.00/kg hydrogen at the plant gate.
- By 2015, research and develop high- and ultra-high-temperature thermochemical/electrical processes to convert hydrogen from high temperature heat sources (nuclear or solar) with a projected cost competitive with gasoline.<sup>2</sup>
- Evaluate other new technologies that have the potential for cost-effective sustainable production of hydrogen and fund appropriate research and development (R&D) in promising areas.

<sup>1</sup> Collaboration with the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Biomass Program. Offsets for coproducts not included.

<sup>2</sup> Collaboration with DOE's Office of Nuclear Energy.

### 3.1.2 Technical Approach

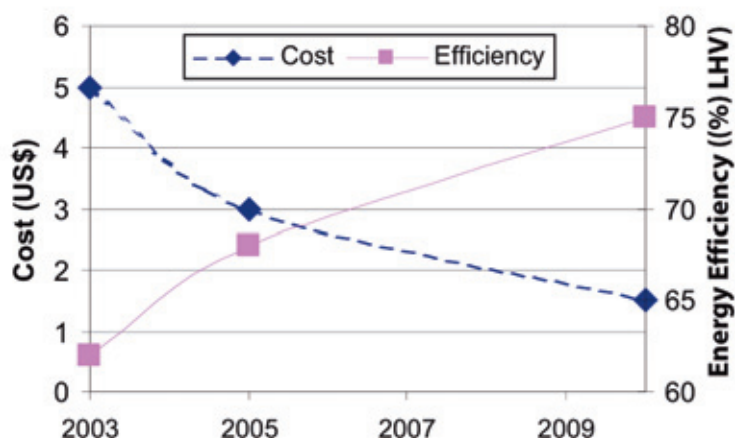
Hydrogen production research is focused on meeting the objectives outlined in Section 3.1.1. by conducting R&D through industry, national laboratory, and university projects.

An array of feedstocks and technologies for hydrogen production will be necessary to address energy security and environmental needs. This program element addresses multiple feedstock and technology options to provide effective and efficient hydrogen production for the short and long terms. There is a focus on distributed production from natural gas and liquid fuels to meet initial lower volume needs with the least capital investment. Some of these liquid fuels can be produced from renewable biomass sources. The focus shifts to renewable feedstock and energy sources for the long term. There is also a strong collaboration with DOE's Office of Fossil Energy to develop centralized production from coal or natural gas with carbon sequestration.

#### Distributed Production Pathway

The development of a national hydrogen production infrastructure could take one or more pathways. A distributed production infrastructure could consist of natural gas or liquid fuel reformers, or electrolyzers located at the point of use, i.e., refueling stations and stationary power generation sites. This approach may be the most viable for introducing hydrogen as an energy carrier. It requires less capital investment for the smaller volume of hydrogen needed initially, and it does not require a substantial hydrogen transport and delivery infrastructure (See Figure 3.1.1). However, carbon sequestration in distributed systems will be difficult and costly because of economies of scale. So, while centralized production benefits from economies of scale, distributed production may reduce hydrogen delivery costs. In the longer term, centralized production will be more cost effective in most cases, but distributed production will still play an important role.

**Figure 3.1.1 Status and Targets for Distributed Hydrogen Production from Natural Gas or Liquid Fuels (from Table 3.1.2)**



#### Centralized Production Pathway

The second approach, which DOE is pursuing in parallel, is to produce hydrogen centrally using any one of a variety of feedstocks, both fossil and renewable. Coal and natural gas are possibly

the least expensive feedstocks, but carbon sequestration is required to reduce or eliminate the high level of greenhouse gas emissions. Gasification or pyrolysis of biomass is a viable approach in many regions of the country. Photoelectrochemical and photobiological hydrogen production are embryonic technologies that have potential to produce hydrogen by splitting water with sunlight, but they can currently only produce small amounts of hydrogen at high cost. Water electrolysis is a viable approach where there is very inexpensive electricity. High- and ultra-high-temperature thermochemical hydrogen production that uses nuclear waste heat or solar heat sources may be viable with the development of appropriate water-splitting chemical process cycles and materials. Other feedstocks and technologies for hydrogen production that show promise may also be considered.

Central production of hydrogen could potentially include a diversified feedstock base, but to be commercially viable it would require development of a distribution infrastructure for hydrogen. The Hydrogen, Fuel Cells & Infrastructure Technologies Program is pursuing projects to identify a cost-effective, energy-efficient, safe infrastructure for the delivery of hydrogen or hydrogen carriers from centrally located production facilities to the point of use. (see Section 3.2.)

### Other Production Pathways

Another pathway being explored is coproduction of hydrogen, heat, and power at Power Parks. In this scenario, hydrogen would be produced for use in a fuel cell to produce electricity and sold for use as a fuel. This allows two markets for the hydrogen in a swing plant operation. This could be useful to initiate the use of hydrogen when hydrogen demand is small. As the demand grows, more of the hydrogen produced could be sold rather than used for power production. (See Section 3.5.)

There are also hybrid hydrogen production options, in which a base feedstock can be centrally transformed to a chemical liquid hydrogen carrier that can be transported at low cost to distributed hydrogen production facilities. For example, naphtha, produced centrally from petroleum, and biomass liquids, such as oil from pyrolysis or ethanol, could be transported to local distributed refueling stations, and then reformed to hydrogen.

At particular points in the development of diverse hydrogen production technologies, DOE will evaluate each approach and concentrate resources on the technologies that have the most potential to meet the goals and objectives.

**Figure 3.1.2 Centralized Hydrogen Production Facility**



**Figure 3.1.3 Hydrogen production via laboratory-scale electrolysis. PIX 03973**



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## Technical Plan – Hydrogen Production

Much of this research is applicable to several of the production options. For example, advanced technology for reforming, shift, hydrogen separations, and hydrogen purification broadly applies to natural gas, coal, and biomass feedstocks and for both distributed and central production situations. Advanced hydrogen separations and purification technology is common to many hydrogen production routes.

The Hydrogen Production program element will develop the technologies to produce hydrogen for transportation and stationary applications. System validations will be performed by the Technology Validation program element (see Section 3.5). Results of validation projects will guide the continuing R&D efforts.

The initial years of the Hydrogen Production program element will require large resources to address the technical barriers. After each milestone is completed, research efforts will refocus on remaining barriers. By 2020, the program element is expected to require only 20% of the resources required in the early years.

### 3.1.3 Programmatic Status

#### Current Activities

Major Hydrogen Production program element activities are listed in Table 3.1.1.

Table 3.1.1. Major Hydrogen Production Program Element Activities		
Challenge	Approach	Activities
Cost reduction of distributed hydrogen production from natural gas and liquid fuels	<ul style="list-style-type: none"><li>• Improve reforming efficiencies</li><li>• Identify more durable reforming catalysts</li><li>• Develop breakthrough separations technology</li><li>• Reduce space needed</li><li>• Optimize system operation</li></ul>	<ul style="list-style-type: none"><li>• <b>Praxair</b>: Oxygen Transport Membrane for reforming followed by Hydrogen Transport Membrane integrated shift reactor</li><li>• <b>Air Products and Chemicals Inc</b>: Hydrogen refueling station using advanced natural gas steam methane reforming technologies</li><li>• <b>General Electric</b>: Fuel-flexible autothermal reformer</li><li>• <b>National Energy Technology Laboratory (NETL)</b>: Advanced water gas shift membrane reactors</li></ul>
Large-scale central production of hydrogen from coal or natural gas with carbon sequestration	<ul style="list-style-type: none"><li>• Develop catalysts and materials for reforming natural gas and producer gas</li><li>• Develop advanced shift technology and separations and purification</li></ul>	<p><b>DOE Fossil Energy (FE) Office</b>: Central natural gas reforming, coal gasification, and carbon sequestration</p> <p><b>EERE in collaboration with FE</b>: Advanced technologies for reforming natural gas and producer gas, shift technology, and separations and purification</p>

Challenge	Approach	Activities
Central production of hydrogen from biomass	<ul style="list-style-type: none"> <li>• Improve gasification and pyrolysis technologies</li> <li>• Develop advanced reforming and shift technologies</li> </ul>	<p><b>National Renewable Energy Laboratory (NREL):</b> Biomass pyrolysis followed by reforming of the resulting bio-oil</p> <p><b>Iowa State University:</b> Indirectly heated gasification system to convert switchgrass into hydrogen, and lab-scale anaerobic fermentation process to convert wastes to hydrogen</p>
Photobiological production of hydrogen	<ul style="list-style-type: none"> <li>• Develop new strains of algae that produce large quantities of hydrogen more efficiently in the presence of sunlight using genetics</li> </ul>	<p><b>NREL, Oak Ridge National Laboratory (ORNL), UC Berkeley, and others:</b> Identification of the physical and chemical variables needed to optimize new photobioreactors based on new algae strains</p>
Photoelectrochemical hydrogen production from water using sunlight and photovoltaics	<ul style="list-style-type: none"> <li>• Develop high-efficiency materials</li> <li>• Improve the durability of materials</li> <li>• Apply basic science understanding to maximize the efficiency and durability of low-cost materials</li> </ul>	<p><b>NREL and others:</b> Durable and cost-effective photoelectrochemical hydrogen production systems</p>
Hydrogen production from water via electrolysis	<ul style="list-style-type: none"> <li>• Lower operating costs by substituting heat energy for electricity using high-temperature electrolysis</li> <li>• Evaluate large- and small-scale hydrogen production using wind and other renewable electricity</li> </ul>	<p><b>Lawrence Livermore National Laboratory (LLNL):</b> High-efficiency steam electrolyzer</p> <p><b>Idaho National Engineering and Environmental Laboratory (INEEL):</b> Improved methods for producing hydrogen via electrolysis</p>
High-temperature (700°C-1000°C) thermochemical water-splitting for production of hydrogen and oxygen	<ul style="list-style-type: none"> <li>• Utilize the high-temperature heat from advanced gas-cooled nuclear reactor technology to split water into hydrogen and oxygen</li> </ul>	<p><b>DOE Office of Nuclear Energy, Science, and Technology:</b> Initial research on high-temperature thermochemical production of hydrogen</p>

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## Technical Plan – Hydrogen Production

Challenge	Approach	Activities
Ultra-high temperature (1000°C -3000°C) thermochemical hydrogen production from water using concentrated solar energy	<ul style="list-style-type: none"> <li>Investigate ultra-high temperature thermochemical technology and other chemical cycles that split water</li> </ul>	<b>NREL and the University of Colorado:</b> Evaluation of solar concentrator driven water splitting
Other hydrogen production, separation, and purification technologies	<ul style="list-style-type: none"> <li>Develop improved separation technology</li> <li>Conduct cross-cutting hydrogen production and delivery analysis</li> </ul>	<b>Westinghouse Savannah River Technology Center:</b> Improved separation technology <b>Sandia National Laboratories (SNL):</b> Defect-free thin ceramic membranes for hydrogen separation and isolation <b>NREL and TIAx, LLC:</b> Evaluation of small-scale purification technologies <b>Longitude 122 West, Inc.:</b> Independent modeling and assessment of integrated hydrogen systems

### 3.1.4 Technical Challenges

The overarching technical challenge to hydrogen production is reducing cost. Hydrogen currently costs \$5/kg delivered to a car at a refueling station (see Table 3.1.2) based on distributed production using natural gas, compared to the goal of \$1.50/kg (untaxed) in 2010. Estimates of the delivered cost of hydrogen using currently available technology for all production feedstocks and technologies are considerably higher than are required for hydrogen to be a cost-competitive primary energy carrier.

Associated with each potential feedstock or energy source are unique challenge and benefit trade-offs. Fossil feedstocks, for example, are widely available and relatively well understood and accepted, but until carbon sequestration becomes feasible, greenhouse gas emissions make fossil feedstocks environmentally difficult. Biomass, on the other hand, has very small net carbon emissions, but presents challenges with feedstock collection, transportation, availability, and storage.

Photobiological hydrogen production is in an early stage of development and presents many technical challenges, beginning with genetic engineering of micro-organisms that can produce hydrogen at high rates. However, the advantages of photobiological hydrogen production are that high-purity water is not required and toxic or polluting byproducts are not generated. Photoelectrochemical hydrogen production, also in an early stage of development, depends on a breakthrough in materials development and could require large areas of land. Research in this area is progressing on two fronts: 1) working on the high efficiency materials in order to apply basic science understanding to lower-efficiency, low-cost materials, and 2) working on the durability of low-cost materials in order to apply basic science understanding to higher-efficiency, lower-durability materials.

The capital costs of electrolysis systems, along with the high cost of electricity and the large greenhouse gas emissions from the current fossil-dominated electric mix in the U.S., limit

widespread adoption of electrolysis technology for hydrogen production. Electrolyzer capital cost reductions, through technology development and system integration with low-cost, emission-free electricity sources, are needed to be competitive with conventional fuels.

High-temperature thermochemical hydrogen production using water-splitting chemical cycles requires significantly more development. Ultra-high-temperature technology using concentrated solar energy water-splitting chemical cycles has not been evaluated. New nuclear energy technology is a possible source of high temperature heat for thermochemical hydrogen production, but this technology is still under development, and time will be needed to site new nuclear plants or adapt existing plants. If these efforts are successful, high-temperature thermochemical processes may provide a clean, efficient, sustainable route for producing hydrogen from water.

### **3.1.4.1 Technical Targets**

A variety of feedstocks and processes are being researched and developed for producing hydrogen fuel. Each technology is in a different stage of development, and each offers unique opportunities, benefits, and challenges. Economics favor certain technologies more than others in the near term, but other technologies are expected to become economically viable as the technologies mature and market conditions shift.

Tables 3.1.2 through 3.1.9 list the DOE technical targets for hydrogen production from a variety of feedstocks. Targets for 2010 are R&D milestones for measuring progress, and are not necessarily the targets required for successful commercialization of the technology. Table 3.1.2 lists the DOE technical targets for distributed hydrogen production from natural gas or liquid fuels. Table 3.1.3 includes technical targets for one membrane system for hydrogen separations and purification from fossil or biomass feedstock. Tables 3.1.4 and 3.1.5 list technical targets for hydrogen production from biomass via gasification with steam reforming and via pyrolysis with steam reforming, respectively. Technical targets for photoelectrochemical and photobiological production of hydrogen are shown in Tables 3.1.6 and 3.1.7, respectively. Tables 3.1.8a and 3.1.8b show the technical targets for hydrogen generation by water electrolysis. Table 3.1.9 lists the technical targets for high-temperature thermochemical hydrogen production.

All targets were developed through preliminary hydrogen production analyses and will be refined further as the technology matures and feedstock trade-offs are identified. Additionally, cost targets will be assessed using more consistent economic assumptions, which are now being developed. The targets and timelines for each technology reflect a number of factors, including the expected size of a production unit, the stage of technology development, and the costs and characteristics of the feedstock. The ultimate goal for each technology is to produce hydrogen at a cost that is competitive with gasoline for transportation applications and with other technologies for stationary power generation.

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## Technical Plan – Hydrogen Production

**Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas and Liquid Fuels**

Characteristics		Units	Calendar Year		
			2003 Status <sup>1</sup>	2005 Target	2010 Target <sup>2</sup>
Reforming	Natural Gas Cost	\$/kg H <sub>2</sub>	0.66	0.62	0.58 <sup>3</sup>
	Other Costs	\$/kg H <sub>2</sub>	3.08	1.36	0.24 <sup>4</sup>
	Primary Energy Efficiency <sup>5</sup>	%(LHV)	70 <sup>6</sup>	72	75
Purification	Cost	\$/kg H <sub>2</sub>	0.17	0.11	0.03
	Hydrogen Efficiency <sup>7</sup>	%(LHV)	75 <sup>8</sup>	82	90
Compression	Cost	\$/kg H <sub>2</sub>	0.34	0.29	0.24
	Primary Energy Efficiency	%(LHV)	82 <sup>9</sup>	85	88
Storage and Dispensing	Cost	\$/kg H <sub>2</sub>	0.25 <sup>10</sup>	0.19	0.11
	Primary Energy Efficiency	%(LHV)	100 <sup>11</sup>	100	100
Other	Cost <sup>12</sup>	\$/kg H <sub>2</sub>	0.50	0.42	0.30
	Primary Energy Efficiency	%(LHV)	100	100	100
Total	Cost	\$/kg H <sub>2</sub>	5.00	3.00	1.50
	Primary Energy Efficiency	%(LHV)	62	68	75

<sup>1</sup> Assumes state-of-the-art technology that is feasible but not necessarily available in a complete system today. This assumption is consistent with the automotive fuel cell performance target assumptions.

<sup>2</sup> Subsystem targets were developed to achieve 75% LHV overall efficiency and \$1.50/kg total cost goals.

<sup>3</sup> Assumes energy cost reductions by way of higher efficiency.

<sup>4</sup> Assumes a 50% equipment cost reduction from the current scenario. These reductions may not be achievable with incremental development of current state-of-the-art technology and will likely require substantial additional technology improvement.

<sup>5</sup> Reforming efficiency calculation includes all the energy inputs to both the primary feed stream and secondary streams such as fuel for generating process heat and power for running essential equipment.

<sup>6</sup> Assuming a steam methane reformer operating at 10 atm.

<sup>7</sup> Hydrogen efficiency is defined as hydrogen output/hydrogen input of the purification process step. Primary energy efficiency is not specified because it is assumed that the purification off-gases (containing CO, CH<sub>4</sub> and unrecovered H<sub>2</sub>) are recycled for use in the reforming step.<sup>8</sup> Assuming a small-scale PSA system operating at reformer outlet pressure.

<sup>9</sup> Assuming conventional compressors are used from the PSA outlet pressure to 3,600 psi maximum on-site storage pressure and accumulator-type compressors are used from the storage pressure to 5,000 psi on-board storage.

<sup>10</sup> Based on 3,600 psi on-site gas storage.

<sup>11</sup> Assuming high-pressure gas storage with no leaks during storage or dispensing.

<sup>12</sup> Includes site preparation and central controls capital costs, operating labor, rent, utilities, and maintenance parts and labor; excludes operator profit.

Notes: Costs are based on a hydrogen refueling station serving 138 vehicles per day (690 kg per day) with on-site production assuming a very high (90%) utilization factor and relatively low capital recovery factor (11%). Much lower utilization factors would be expected during the early years of fuel cell vehicle introduction. Capital equipment costs for the 2005 and 2010 targets assume mature production volumes of 100 units per year. The current status reflects the cost of using current state-of-the-art available technology and assembling it into a single unit. Energy costs assume a natural gas price of \$4/MMBtu (HHV) and power price of \$0.07/kWh. Primary energy efficiency is defined as Hydrogen Output LHV / Energy Input LHV of the process step. Input energy associated with on-site power use assumes a 35% production and transmission efficiency penalty (typical US grid mix).

**Table 3.1.3. Technical Targets: Separation Membranes for Hydrogen Production with Palladium Membranes**

Characteristics	Units	Calendar Year		
		2003 Status <sup>2</sup>	2005 Target	2010 Target
Flux Rate <sup>1</sup>	scfh/ft <sup>2</sup>	60	100	200
Cost	\$/ ft <sup>2</sup>	\$150-\$200	\$100-\$150	<\$100
Durability	hours <sup>3</sup>	<1,000 <sup>4</sup>	50,000	100,000
Operating Temp	°C	300-600	300-600	300-600
Parasitic Power <sup>5</sup>	kWh/ 1,000 scfh	3.2	3.0	2.8

<sup>1</sup> Flux at 20 psi hydrogen partial pressure differential and 400 °C.

<sup>2</sup> Based on membrane shift reactor with syngas.

<sup>3</sup> Intervals between membrane replacement.

<sup>4</sup> Hydrogen membranes have not been demonstrated to date, only laboratory tested.

<sup>5</sup> These parasitic power requirements are based on the power required to recompress the hydrogen to 200 psi downstream of the membrane due to the pressure drop across the membrane.

Notes: Targets are based on a palladium membrane that is fuel neutral and can be used for hydrogen separation and purification from a variety of fuels. Although these membranes can be used for both separation and purification, the opportunity to develop other novel H<sub>2</sub> separation and purification technologies will not be precluded. Advances in microporous membranes and ion transport membranes, for example, are expected.

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## Technical Plan – Hydrogen Production

**Table 3.1.4. Technical Targets: Central Hydrogen from Biomass via Gasification and Steam Reforming**

Characteristics		Units	Calendar Year			
			2003 Status <sup>1</sup>	2005 Target	2010 Target <sup>2</sup>	2015 Target
Biomass feed <sup>3</sup>	Cost	\$/kg H <sub>2</sub>	0.80	0.70	0.60	0.50
Operations through gasification <sup>4</sup>	Cost	\$/kg H <sub>2</sub>	1.60	1.50	1.20	1.00
	Energy Efficiency	% (LHV)	68	69	75	82
Reforming <sup>5</sup>	Cost	\$/kg H <sub>2</sub>	0.50	0.50	0.40	0.20
	Energy Efficiency	% (LHV)	85	86	89	93
Purification <sup>6</sup>	Cost	\$/kg H <sub>2</sub>	0.40	0.40	0.30	0.30
	Energy Efficiency	% (LHV)	74	74	77	82
Total	Cost <sup>7</sup>	\$/kg H <sub>2</sub>	3.60	3.30	2.60	2.00
	Net Energy Ratio <sup>8</sup>		28	29	34	41

<sup>1</sup> Current status of capital cost for gasification section assumed to be 30% greater than those predicted in Spath and Mann (2000) for 2010, according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Incremental improvement through 2005 is assumed. Current reforming costs are assumed to be 50% higher than those in 2010.

<sup>2</sup> Capital cost for gasification, reforming, and purification sections for 2010 taken from Spath and Mann, 2000.

<sup>3</sup> Biomass cost in 2010 = \$42/bone dry ton. Feedstock costs for other years based on relative total process efficiencies.

<sup>4</sup> Includes biomass handling and drying, gasification, and compression prior to the reformer, plus associated fixed and non-feedstock variable operating costs. Capital costs for gasification are according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Gasification costs in 2020 assume innovative process design, such as integrated gasification/reforming.

<sup>5</sup> Includes steam reforming reactor, high temperature shift reactor, low temperature shift reactor, and heat exchangers between reactors. Includes associated fixed and non-feedstock variable operating costs. Efficiency includes generation of coproduct steam.

<sup>6</sup> Assumes commercially available pressure swing adsorption (PSA). Includes associated fixed and nonfeedstock variable operating costs. Source: Spath and Mann, 2000.

<sup>7</sup> Total cost is for low-pressure (300 psi) hydrogen, at the plant gate.

<sup>8</sup> Net energy ratio is defined as the amount of energy in the product hydrogen, divided by the fossil energy consumed within the system (including feedstock production and delivery, equipment manufacture, grid electricity production used by the system, and waste disposal). Because biomass is a renewable resource, the energy it contains is not considered to be consumed. Calculations made from Mann and Spath, 1997, Life Cycle Assessment of a Combined Cycle Power System, NREL/TP-430-23076, National Renewable Energy Laboratory.

Costs are for a projected biomass gasification/steam reforming plant, processing 1,046 bone dry Mg/day biomass, with a capacity of 75,000 kg H<sub>2</sub>/day.

Research is required to achieve the cost targets (see Section 3 – Technical Challenges, and Section 3.4 – Hydrogen Production from Biomass Technical Barriers).

**Table 3.1.5. Technical Targets: Central Hydrogen from Biomass via Pyrolysis and Steam Reforming**

Characteristics		Units	Calendar Year			
			2003 Status <sup>1</sup>	2005 Target	2010 Target <sup>2</sup>	2015 Target
Biomass feed <sup>3</sup>	Cost	\$/kg H <sub>2</sub>	0.80	0.80	0.70	0.60
Operations through pyrolysis <sup>4</sup>	Cost	\$/kg H <sub>2</sub>	1.90	1.90	1.50	1.20
	Energy Efficiency	% (LHV)	65	66	72	79
Reforming <sup>5</sup>	Cost	\$/kg H <sub>2</sub>	0.70	0.60	0.40	0.30
	Energy Efficiency	% (LHV)	83	84	87	91
Purification <sup>6</sup>	Cost	\$/kg H <sub>2</sub>	0.40	0.40	0.30	0.30
	Energy Efficiency	% (LHV)	74	74	77	82
Total	Cost <sup>7</sup>	\$/kg H <sub>2</sub>	3.80	3.70	2.90	2.40
	Net Energy Ratio <sup>8</sup>		26	27	32	39

<sup>1</sup> Current status of capital cost for pyrolysis section assumed to be 30% greater than that predicted in Spath and Mann (2000) for 2010, according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Incremental improvement through 2005 is assumed. Current reforming cost is assumed to be 50% higher than that in 2010.

<sup>2</sup> Capital cost for reforming and purification sections for 2010 taken from Spath and Mann, 2000.

<sup>3</sup> Biomass cost in 2010 = \$42/dry ton.

<sup>4</sup> Includes biomass handling and drying, pyrolysis, and delivery of prepared pyrolysis oil to a central reformer, plus associated fixed and non-feedstock variable operating costs. Capital costs for pyrolysis are based on reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997.

<sup>5</sup> Includes steam reforming reactor, high temperature shift reactor, low temperature shift reactor, and heat exchangers between reactors. Includes associated fixed and non-feedstock variable operating costs. Efficiency includes generation of coproduct steam.

<sup>6</sup> Assumes commercially available PSA. Includes associated fixed and nonfeedstock variable operating costs. Source: Spath and Mann, 2000.<sup>7</sup> Total cost is for low-pressure (300 psi) hydrogen, at the plant gate.

<sup>8</sup> Net energy ratio is defined as the amount of energy in the product hydrogen, divided by the fossil energy consumed within the system (including feedstock production and delivery, equipment manufacture, grid electricity produced for use by the system, and waste disposal). Because biomass is a renewable resource, the energy it contains is not considered to be consumed.

Costs are for a projected biomass pyrolysis/steam reforming operation, processing a combined total of 1,112 bone dry Mg/day biomass, with a capacity of 75,000 kg H<sub>2</sub>/day. Several small pyrolysis units are assumed to be located near the source of the biomass residue, providing pyrolysis oil to a central reformer. Primary source is Spath and Mann, 2000, NREL/MP-33112, National Renewable Energy Laboratory. Cost projections assume no coproduct; coproduct opportunities may significantly reduce final cost, while providing market flexibility and heat integration savings.

Research is required to achieve the cost targets (see Section 3.1.4 – Technical Challenges, and Section 3.1.4.2.2 – Hydrogen Production from Biomass Technical Barriers).

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## Technical Plan – Hydrogen Production

**Table 3.1.6. Technical Targets: Photoelectrochemical Hydrogen Production**

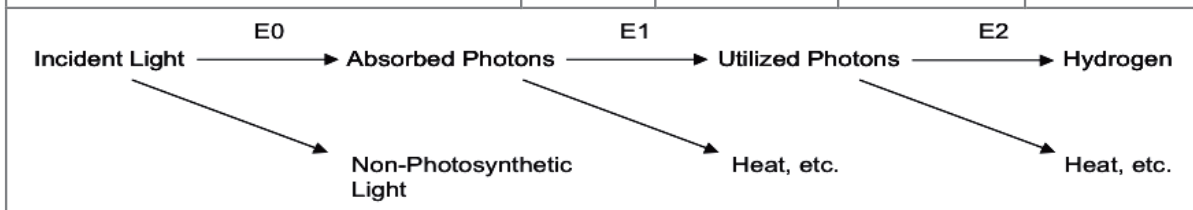
Characteristics	Units	2003 Status	2005 Target	2010 Target	2015 Target
Solar-to-Hydrogen Efficiency	%	7	7.5	9	14
Durability	hours	100	1,000	10,000	20,000
Cost <sup>1</sup>	\$/kg	N/A <sup>2</sup>	360	22	5

<sup>1</sup> Costs are for low-pressure hydrogen, at the plant-gate. Primary source is Mann, Spath, and Amos: Technoeconomic Analysis of Different Options for the Production of Hydrogen from Wind, Solar, and Biomass, Proceedings of the 1998 U.S.DOE Hydrogen Program Review, NREL/CP-570-25315. Costs were projected from the reference report by scaling linearly with durability and inversely with efficiency.

<sup>2</sup> Currently, the highest efficiency systems have the shortest lifetime, and the lower efficiency systems have the longest lifetimes. The optimum system will likely be a compromise between efficiency and lifetime. It is inappropriate to estimate current system cost given the current demonstrated durability results for the higher efficiency materials.

**Table 3.1.7. Technical Targets: Photobiological Hydrogen Production**

Characteristics	Units	2003 Status	2005 Target <sup>1</sup>	2010 Target <sup>2</sup>
Utilization Efficiency of Absorbed Light Energy (E1)	%	~5	10	20
Absorbed Light Energy to Hydrogen Efficiency (E1*E2)	%	0.1	0.5	5
Duration of Continuous Photoproduction <sup>3</sup>	hours	240	500	1500
Cost <sup>4</sup>	\$/kg	200	100	30



E0 reflects light collection efficiency of the photobioreactor and the fact that only a fraction of incident light is photosynthetically active.

E1 is the efficiency with which algae convert the energy of absorbed photons to chemical energy (i.e. electrons).

E2 reflects the efficiency with which this chemical energy is converted to hydrogen.

E1 and E2 represent peak efficiencies.

<sup>1</sup> 2005 target is based on analysis of best technologies available, theoretically integrated into a single organism.

<sup>2</sup> 2010 target is based on analysis of best technologies available, physically integrated into a single organism.

<sup>3</sup> E1 and E2 represent peak efficiencies. Duration reflects continuous production, not necessarily at peak efficiencies.

<sup>4</sup> Costs are for low-pressure hydrogen, at the plant-gate. Primary source is Amos, Wade: Cost Analysis of Photobiological Hydrogen Production from Chlamydomonas reinhardtii Green Algae, NREL milestone report, September 2000. Cost projections were modified to reflect research advancements toward continuous hydrogen production systems.

**Table 3.1.8a. Technical Targets: Water Electrolysis<sup>1</sup>**

Characteristics		Units	250 kg/day Refueling Station <sup>1</sup>			Small-Scale Refueling <sup>2</sup> : 2 kg/day		
			Calendar Year			Calendar Year		
			2003 Status	2005 Target	2010 Target	2003 Status	2005 Target	2010 Target
Power Conversion	Cost <sup>3</sup>	\$/kg	0.38	0.28	0.08	0.32	0.21	0.12
	Energy Efficiency	% (LHV)	95	96	98	95	96	98
Cell Stack	Cost	\$/kg	0.64	0.48	0.25	1.37	0.79	0.30
	Energy Efficiency	% (LHV)	72	76	81	65	70	79
Balance of Plant <sup>4</sup>	Cost	\$/kg	0.13	0.13	0.07	0.21	0.14	0.10
	Energy Efficiency	% (LHV)	98	98	98	97	97	98
Compression <sup>5</sup>	Cost	\$/kg	0.47	0.32	0.16	0.34	0.21	0.09
	Energy Efficiency	% (LHV)	90	92	95	83	90	93
Storage and Dispensing	Cost <sup>6</sup>	\$/kg	0.19	0.14	0.06	0.21	0.16	0.12
	Energy Efficiency	% (LHV)	99	99	99	99	99	99
Electricity <sup>7</sup>	Cost	\$/kg	1.90	1.80	1.60	4.10	3.30	2.80
Total	Cost <sup>8</sup>	\$/kg	4.70	3.80	2.50	7.40	5.30	3.80
	Energy Efficiency	% (LHV)	60	65	73	49	58	70

<sup>1</sup> Distributed electrolyzer at a refueling station delivering 250 kg of hydrogen per day at 5,000 psig.

<sup>2</sup> Home/distributed refueling station delivering 2 kg of hydrogen per day at 5,000 psig.

<sup>3</sup> Cost reductions reflect possible direct integration with renewable DC electricity or improved power conversion technology.

<sup>4</sup> Includes hydrogen purification and water removal.

<sup>5</sup> Compression improvements result from integral electrochemical or other system compression to reduce one or more mechanical compression stages.

<sup>6</sup> Cost reduction in 2010 based on system optimization to reduce storage costs and possible low cost storage options.

<sup>7</sup> Off-peak or low-cost renewable energy at \$0.035 per kWh and 40% capacity factor for large system, \$0.06 per kWh and 95% utilization for small home refueling system.

<sup>8</sup> Based on system capital cost of \$750, \$600, and \$300 per kWe for refueling stations and \$2000, \$1500, and \$800 for small-scale refueling systems per kWe, respectively. Includes O&M, labor and physical plant construction, 15% IRR, 20-year equipment life. Total costs are rounded to the nearest dime.

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## Technical Plan – Hydrogen Production

**Table 3.1.8b. Technical Targets: Centralized Hydrogen Production by Electrolysis<sup>1</sup>**

Characteristics		Units	2003 Status	2005 Target	2010 Target
Power Conversion	Cost <sup>2</sup>	\$/kg	0.10	0.07	0.03
	Energy Efficiency	% (LHV)	95	96	98
Cell Stack	Cost	\$/kg	0.18	0.13	0.06
	Energy Efficiency	% (LHV)	72	76	82
Balance of Plant <sup>3</sup>	Cost	\$/kg	0.04	0.04	0.02
	Energy Efficiency	% (LHV)	98	98	99
Electricity <sup>4</sup>	Cost	\$/kg	2.00	2.00	1.90
Total	Cost <sup>5</sup>	\$/kg	2.80	2.50	2.00
	Energy Efficiency	% (LHV)	67	72	80

<sup>1</sup> 1000 kg per day electrolyzer producing hydrogen at 100-500 psi at plant gate. (Modular units can be scaled to utility size applications.)

<sup>2</sup> Cost reductions reflect development in power conditioning/control.

<sup>3</sup> Includes purification and water removal.

<sup>4</sup> Electricity at \$0.045 per kWh and 95% capacity factor (based on nuclear, hydro, or other renewable integrated electricity, steam electrolysis would have lower electricity and include cost for steam).

<sup>5</sup> Based on system capital cost of \$400, \$300, and \$150 per kWe, respectively. Includes O&M cost, labor, and physical plant construction, 15% discount rate, 20-year equipment life.

Note: Capital costs for steam electrolysis would be higher, electricity costs lower, and efficiency higher. The goal of large scale electrolysis technologies is to reach the \$2.00 per kg cost by 2010 and longer range goal of \$1.50 per kg at the plant gate.

Table 3.1.9. High- and Ultra-High-Temperature Thermochemical Hydrogen Production

Characteristics		Units	2003 Status	2005 Target	2010 Target
High-Temperature Production <sup>1</sup>	Cost at the plant gate	\$/kg	NA <sup>2</sup>	10	2
	Energy Efficiency	%	NA <sup>2</sup>	25	40
Ultra-High Temperature Solar Production <sup>3</sup>	Cost at the plant gate	\$/kg	12	8	4
	Solar concentrator cost	\$/m <sup>2</sup>	250	130	75
Process efficiency <sup>4</sup>		%	20	40	45

<sup>1</sup>This is based on large scale central production of hydrogen using waste heat from next generation nuclear energy at 700-900°C using a chemical cycle/water splitting process such as the sulfur-iodide chemical cycle. It is based on plant gate costs at low pressure (~200 psig). Few and only very rough cost estimates of this technology have been done with one published by General Atomics that projects an ultimate possible cost of as low as \$1.00/kg of hydrogen. The targets set for 2005 and 2010 are based on estimates of progress that need to be made to achieve the objective of \$1.00/kg by 2015.

<sup>2</sup> Nuclear-based thermochemical cycles are an unproven technology with insufficient information for current estimates.

<sup>3</sup> Based on estimates for a concentrated solar driven thermal methane splitting process. The cost evaluation is documented in "Assessment of Natural Gas Splitting with a Concentrating Solar Reactor for Hydrogen Production"; April 2002, Pamela Spath and Wade Amos; NREL/TP-510-31949. The values in this Table are based on the work done as part of that report and projecting the required technology improvements from what has currently been achieved at NREL on this process and on solar concentrators. These targets serve as guideposts for ultra-high temperature solar concentrated driven hydrogen production technologies such as possible chemical cycle water splitting processes.

<sup>4</sup> Defined as the energy to drive the reaction divided by incident direct sunlight on the concentrators.

Note: These technologies are at the early stage of exploration. The targets below are rough guidelines only. The long-term goal (2015) is for the hydrogen produced from these technologies to be cost competitive with gasoline delivered at the refueling station or stationary power facility.

### 3.1.4.2 Barriers

The following sections detail the technical and economic barriers that must be overcome to attain the Hydrogen Production goal and objectives. The barriers are divided into sections depending on the hydrogen production method.

#### 3.1.4.2.1 Distributed Hydrogen Production from Natural Gas or Liquid Fuels Barriers

**A. Fuel Processor Capital Costs.** Current small-scale distributed natural gas or liquid fuel reformer technologies are too expensive to supply hydrogen at a cost comparable to that of gasoline. Multiple unit operations and insufficient heat integration contribute to large, costly production and purification subsystems. Improved reforming and shift catalysts are needed to reduce side reactions and improve performance, bearing in mind the availability of the catalyst materials. Shift, separation, and purification step costs need to be reduced by developing new technology such as single-step shift with integrated membrane technology to shift, separate, and purify the hydrogen in one step.

- B. Operation and Maintenance (O&M).** O&M costs for distributed hydrogen production from natural gas or liquid fuels are too high. Systems need to be optimized to reduce labor costs and spare part requirements.
- C. Feedstock and Water Issues.** Distributed hydrogen production relies on local availability of resources, which may pose limitations in certain areas. Technologies and strategies for water clean up are needed to avoid intolerable impurities in reformer steam. Feedstock-flexible reformers are needed to mitigate and/or take advantage of price fluctuations and to address location-specific feedstock supply issues.
- D. Carbon Dioxide Emissions.** Distributed reformers emit greenhouse gases. Cost-effectively sequestering these smaller volume carbon emissions is significantly more challenging than at central hydrogen production facilities that use fossil fuels. This production route should remain limited unless biomass-based liquid fuels are used or until some cost-effective carbon sequestration option for distributed production is discovered.
- E. Control and Safety.** Various control and safety issues are associated with natural gas and liquid fuel reforming, not the least of which is associated with on-off cycling. Effective operations control strategies are needed to minimize cost and emissions, maximize efficiencies, and enhance safety for hydrogen consumers and plant operators.

#### **3.1.4.2.2 Hydrogen Production from Biomass Barriers**

- F. Feedstock Cost and Availability.** Hydrogen produced from biomass is not currently cost competitive with gasoline because feedstock and capital costs are too high. Improved feedstock/agriculture technology (higher yields per acre, etc.); lower cost feedstock collection, transportation, and storage options; and improved feedstock preparation are needed (tasks to overcome these barriers will be developed by other agencies and other DOE programs). Because biomass feedstocks are often seasonal in nature, feedstock-flexible processes and/or cost effective feedstock storage are needed to operate year round.
- G. Efficiency of Gasification, Pyrolysis, and Reforming Technology.** Better heat integration, higher gasification pressures, better feedstock handling, improved gas clean up and conditioning (in gasification systems), and improved vapor conditioning (in pyrolysis systems) are needed. Other areas for reforming technology improvements include improved catalysts, heat integration, and reactor configuration for improved yield.
- H. Fermentative Micro-organisms.** Fermentative micro-organisms for hydrogen production have not been adequately evaluated. This area needs to be investigated further.

#### **3.1.4.2.3 Photobiological and Photoelectrochemical Hydrogen Generation Barriers**

These technologies are not mature. Several technical barriers must be overcome before economic barriers can be considered. Methods of engineering and manufacturing these systems have not been fully evaluated.

- I. Light Utilization Efficiency.** The micro-organisms used for photobiological hydrogen generation possess large arrays of light-capturing antenna chlorophyll (Chl) molecules. Under bright sunlight, this Chl antenna absorbs much more light than can be utilized

by photosynthetic electron transport, resulting in heat dissipation and loss of up to 80% of the absorbed light. Research is needed to identify ways to increase the light conversion efficiency, including the identification of better and/or modified algae for hydrogen production.

- J. Rate of Hydrogen Production.** The current hydrogen production rate from photosynthetic micro-organisms is far too low for commercial viability. Changes to these organisms, such as the genetic insertion of a proton channel into the thylakoid membrane, are required to overcome the restricting metabolic pathways to significantly increase the rate of hydrogen production.
- K. Continuity of Photoproduction.** Hydrogen-producing algae coproduce oxygen, which inhibits the hydrogen producing enzyme. This inhibition needs to be reduced or eliminated, possibly by separating the oxygen and hydrogen production organism cycles using two separate bioreactors and/or by identifying a less oxygen-sensitive enzyme.
- L. Systems Engineering.** Analysis is needed to identify possible barriers to the cost-effective implementation of photobiological hydrogen generation technologies, such as hydrogen collection systems, continuous bioreactor operation, coproduct opportunities, land area requirements and capital costs.
- M. Material Durability.** Durable materials with the appropriate characteristics for photoelectrochemical hydrogen production that meet the Hydrogen Production program element goals have not been identified. The high-efficiency materials currently available corrode quickly during operation. The most durable materials are very inefficient for hydrogen production.
- N. Materials and System Engineering.** Hybrid designs that combine multiple layers of materials could address issues of durability and efficiency. Techniques for manufacturing appropriate photoelectrochemical materials at commercial scale are needed. Reactor designs using cost-effective, hydrogen-impermeable, transparent materials are also needed to implement photolytic production routes.
- O. Photoelectrochemical Efficiency.** Materials with appropriate bandedge and bandgap for hydrogen production must be developed. Materials with smaller bandgaps more efficiently utilize the solar spectrum, but are often less energetically favorable for hydrogen production because of the bandedge mismatch with respect to either hydrogen or oxygen redox potentials.
- P. Diurnal Operation Limitations.** Photolytic processes lose efficiency because they depend on sunlight, which is unavailable at night and available only at low intensities on cloudy days. This results in increased capital costs for larger facilities to accommodate higher instantaneous production rates and larger hydrogen storage needs. Engineering options need to be carefully analyzed to minimize capital requirements.

#### **3.1.4.2.4 Hydrogen Generation by Water Electrolysis Barriers**

- Q. Cost.** The capital costs of electrolysis systems, combined with the high cost and greenhouse gas emissions of electricity from the grid in many locations, are prohibitive to widespread adoption of electrolysis technology for hydrogen production. R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital while improving the efficiency and durability of the system. Systems need to be optimized to minimize O&M costs, including water feed, compression, and cell stack maintenance.

**R. System Efficiency.** Mechanical high-pressure compression technology exhibits low energy efficiency and often reduces hydrogen purity while adding significantly to the system cost. Large efficiency gains can be realized using electrochemical compression in the cell stack. Low-cost, high-pressure materials need to be developed to provide integral electrochemical or other high-pressure compression technologies to replace some or all mechanical compression stages. Development is needed for low-cost cell stack optimization considering efficiency, electrochemical compression, and durability.

**S. Grid Electricity Emissions.** The current grid electricity mix in most locations increases greenhouse gas emissions in large-scale electrolysis systems. Low-cost, carbon-free electricity sources are needed.

**T. Renewable Integration.** More efficient integration with renewable electricity sources is needed to reduce costs and improve performance. Development of small- and large-scale integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production. Novel concepts for carbon-free electrolytic hydrogen production need to be evaluated.

**U. Electricity Costs.** High-temperature solid oxide electrolysis can use lower cost energy in the form of steam for water splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated.

### **3.1.4.2.5 High- and Ultra-High-Temperature Thermochemical Production of Hydrogen Barriers<sup>3</sup>**

This technology is not mature. Several technical barriers must be overcome. Methods of engineering and manufacturing these systems have not been fully evaluated.

**V. High- and Ultra-High-Temperature Thermochemical Technology.** High-purity hydrogen production from the proposed water-splitting chemical cycles and direct water-splitting technology has not been proven. Thermochemical technology components and subsystems have not been evaluated.

**W. High-Temperature Materials.** Very high temperatures are employed in these thermochemical systems. Cost-effective, durable materials are needed that can withstand these high temperatures and the thermal cycling duty cycles that are present in the solar concentrator systems.

**X. Policy and Public Acceptance.** Nuclear restrictions and difficult permitting and licensing procedures severely limit the ability to build nuclear facilities. Permitting and licensing procedures need to be improved, and the public needs to be better educated about the safety issues and potential advantages of nuclear energy systems.

**Y. Solar Capital Cost.** Solar energy collection is currently expensive and requires large areas of land. Improved, lower-cost solar concentrator/collection technology, including materials, is needed.

<sup>3</sup> DOE's Office of Nuclear Energy has the lead responsibility for hydrogen production utilizing nuclear energy for high temperature (700°-1000°C) thermochemical water splitting chemical cycles. The Office of Hydrogen, Fuel Cells, and Infrastructure Technologies will collaborate with Nuclear Energy the high and ultra-high thermochemical hydrogen production R&D activities.

### **3.1.4.2.6 General (Cross Cutting) Hydrogen Production Barriers**

- Z. Catalysts.** Reforming and shift catalysts are not sufficiently durable, efficient, or impurity tolerant. Improved catalysts need to be developed and optimized.
- AA. Oxygen Separation Technology.** Commercial oxygen separation technology relies on expensive and energy-intensive cryogenic separation. Low-cost membrane technology needs to be developed.
- AB. Hydrogen Separation and Purification.** Effective, high flux rate, lower cost, durable hydrogen separation and purification membranes need to be developed. Improved technology for more cost-effective and efficient hydrogen purification is needed. This could include improved PSA technology, the use of membranes to replace PSA technology, and ultimately combining membrane separation and purification with the shift reaction in one unit operation.
- AC. High-Purity Water Availability.** Impacts on water supplies are not understood. Further analysis is needed.
- AD. Market and Delivery.** There is currently no high-volume market for high-purity hydrogen. A feedstock/production strategy and cost-effective delivery systems need to be developed. A market introduction strategy needs to be developed.

### **3.1.5 Technical Task Descriptions**

The technical task descriptions are presented in Table 3.1.10. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate program element. The duration of each task and the barriers associated with it (see Section 3.1.4.2) appear after the task title.

**Table 3.1.10. Technical Task Descriptions**

Task	Description	Duration/Barriers
<b>1</b>	<b>Distributed Production Feedstock Options</b> <ul style="list-style-type: none"> <li>Analyze and research options for alternative feedstocks in addition to natural gas (e.g., ethanol, methanol, sorbitol, naphtha) for distributed production.</li> </ul>	6 Quarters/ Barriers A, C, D, AD
<b>2</b>	<b>Low-Cost, Low-Volume Distributed Production of Hydrogen from Natural Gas or Liquid Fuels</b> <ul style="list-style-type: none"> <li>Develop and test small-scale, advanced fuel-flexible reformer technology for greater efficiency, selectivity, and durability.</li> <li>Develop small-scale advanced shift technology that is more robust over a wider range of operating conditions, including single-step shift with integral hydrogen separation.</li> <li>Develop small-scale, efficient, low-cost separation technology that produces high-purity hydrogen for PEM fuel cells.</li> <li>Develop stand-alone commercial hydrogen refueling station that will store, meter, and dispense hydrogen into fuel cell vehicles.</li> </ul>	12 Quarters/ Barriers A, B, C, D, E, Z, AB
<b>3</b>	<b>Advanced Distributed Hydrogen Production</b> <ul style="list-style-type: none"> <li>Develop efficient, integrated, compact, durable production unit focusing on thermal integration, operational flexibility, design for assembly and low maintenance costs, including low cost installation.</li> <li>Optimize O&amp;M by monitoring facilities remotely.</li> <li>Employ Design for Manufacture and Analysis (DFMA) techniques to develop small-scale reformers.</li> </ul>	16 Quarters/ Barriers A, B, C, D, E, Z, AB
<b>4</b>	<b>Advanced Systems for Oxygen Separations and Reforming</b> <ul style="list-style-type: none"> <li>Improve existing air separation technologies and identify novel technologies for separating oxygen for gasification and reforming.</li> <li>Develop integrated oxygen membrane/reactor systems for reforming.</li> <li>Develop more efficient and impurity-tolerant reforming catalysts.</li> </ul>	24 Quarters/ Barriers A, B, D, E, G, Z, AA
<b>5</b>	<b>Cost Reduction of Pyrolysis Technologies</b> <ul style="list-style-type: none"> <li>Identify opportunities for reducing the cost of biomass pyrolysis technologies, feedstock handling, heat integration, vapor conditioning, and development of coproduct opportunities.</li> <li>Integrate reforming and shift processes.</li> </ul>	20 Quarters/ Barriers F, G, Z, AA, AB

6	<b>Cost Reduction of Biomass Gasification</b> <ul style="list-style-type: none"> <li>Evaluate options for cost reduction, such as high-pressure gasification (10–30 atm), improved heat integration, and novel feedstock preparation and handling systems.</li> <li>Develop and test gasification technologies based on opportunities identified in evaluation.</li> <li>Integrate reforming and shift processes.</li> </ul>	20 Quarters/ Barriers F, G, Z, AA, AB
7	<b>Gasifier Product Gas Clean Up</b> <ul style="list-style-type: none"> <li>Research and develop more cost-effective, efficient, and durable biomass and coal gasifier product gas clean up technologies for feed into reforming operations, including hot-gas clean-up, tar cracking, and other related technologies. (EERE will coordinate with the Office of Fossil Energy on the coal-gasifier product gas clean up technologies.)</li> </ul>	20 Quarters/ Barriers F, G
8	<b>Advanced Biomass Reforming</b> <ul style="list-style-type: none"> <li>Develop advanced catalysts for fluid-bed reforming of biomass pyrolysis liquid.</li> <li>Investigate opportunities for catalyst improvement for reforming and conditioning of biomass gasifier producer gases and pyrolysis oil vapors and fractions.</li> <li>Investigate other reformer improvements, including heat integration and reactor configuration.</li> </ul>	28 Quarters/ Barriers G, Z
9	<b>Advanced Shift Technologies Including Catalyst Development</b> <ul style="list-style-type: none"> <li>Investigate alternative CO shift pathways.</li> <li>Develop advanced shift catalysts that are more efficient and impurity tolerant.</li> <li>Evaluate pathways for improving conventional water-gas-shift catalysts and reactors, including single-stage shift.</li> <li>Conduct water-gas-shift reaction using a high-temperature membrane without added catalyst.</li> <li>Develop integrated single step shift/membrane separation technology.</li> </ul>	28 Quarters/ Barriers A, B, C, D, E, G, Z, AB
10	<b>Basic Research on Advanced Hydrogen Purification</b> <ul style="list-style-type: none"> <li>Examine advanced hydrogen purification systems, including PSA, membranes, and alternatives.</li> <li>Identify low-cost materials for hydrogen purification.</li> <li>Use molecular sieves to stabilize membranes.</li> </ul>	12 Quarters/ Barriers A, B, C, E, G, AB
11	<b>Applied Research on Advanced Hydrogen Purification</b> <ul style="list-style-type: none"> <li>Develop and test advanced hydrogen purification systems that meet cost and efficiency targets.</li> </ul>	16 Quarters/ Barriers A, B, C, E, G, AB

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<b>12</b>	<b>Fermentation Options for Converting Renewable Biomass Resources to Hydrogen</b> <ul style="list-style-type: none"> <li>Evaluate options for converting renewable biomass resources to hydrogen using fermentation.</li> <li>Develop and test fermentation technologies for converting renewable biomass resources to hydrogen.</li> </ul>	28+ Quarters/ Barriers H
<b>13</b>	<b>Molecular Genetics of Organisms for Photobiological Hydrogen Production</b> <ul style="list-style-type: none"> <li>Use high-throughput screening methods to select organisms that are oxygen tolerant, have increased light conversion efficiency, and that allow more efficient photosynthetic electron transport.</li> <li>Research and develop a system that physically separates algal oxygen and hydrogen production.</li> </ul>	28+ Quarters/ Barriers I, J, K
<b>14</b>	<b>System Engineering for Photobiological Hydrogen Production</b> <ul style="list-style-type: none"> <li>Optimize reactor and system designs.</li> <li>Develop hydrogen collection and oxygen separation technologies.</li> <li>Verify economic and technical viability of continuous hydrogen production.</li> </ul>	28+ Quarters/ Barriers I, K, L
<b>15</b>	<b>Development of Semiconductor Materials and Durability Testing</b> <ul style="list-style-type: none"> <li>Use combinatorial or other screening methods to identify semiconductors that meet cost, durability, and efficiency targets.</li> <li>Discover and evaluate materials for device lifetime and demonstrate 1,000 hours of operation as proof of feasibility.</li> <li>Identify and develop coatings to resist corrosion.</li> <li>Evaluate electrolyte options for improved semiconductor durability and efficiency.</li> <li>Develop accelerated screening protocols to predict material durability.</li> </ul>	28+ Quarters/ Barriers M
<b>16</b>	<b>System Engineering of Photoelectrochemical Hydrogen Production</b> <ul style="list-style-type: none"> <li>Evaluate system configurations, including hybrid and other advanced designs, to improve efficiency and durability.</li> <li>Discover/develop cost-effective, transparent, hydrogen-impermeable materials for photolytic hydrogen production.</li> <li>Design reactor systems to optimize light-capture efficiency, hydrogen production, and gas collection.</li> </ul>	24 Quarters/ Barriers M, N, O
<b>17</b>	<b>Transparent Hydrogen-Impermeable Materials for Photolytic Hydrogen Production</b> <ul style="list-style-type: none"> <li>Discover and develop cost effective transparent, hydrogen-impermeable materials for photolytic production of hydrogen.</li> </ul>	20 Quarters/ Barriers N

18	<p><b>Advanced Electrolysis Technologies to Reduce Cost and Increase Efficiency</b></p> <ul style="list-style-type: none"> <li>• Reduce cell stack cost by developing lower cost durable materials with improved manufacturing capability optimized for efficiency, durability, and stack compression.</li> <li>• Develop electrochemical and other novel compression technologies, integral to cell stacks, to reach hydrogen output pressures greater than 500 psi using low-cost materials.</li> <li>• Optimize electrolysis with renewable energy systems to lower cost of power conversion and other system components.</li> <li>• Develop lower cost, durable small-scale distributed systems with 70% (LHV) system efficiency.</li> <li>• Develop utility-scale electrolysis system suitable for renewable electricity integration.</li> <li>• Develop system components for lower system O&amp;M costs including water feed, cell stack durability, and compression.</li> <li>• Evaluate steam electrolysis for improving efficiency, reducing electricity cost, and improving system durability.</li> <li>• Continue development of reversible solid oxide electrolyzer materials and system design.</li> </ul>	28 Quarters/ Barriers Q, R, T, U, AC
19	<p><b>High-Temperature Thermochemical Process Options (700°-1000°C)</b></p> <ul style="list-style-type: none"> <li>• Develop a viable integrated thermochemical water-splitting cycle.</li> <li>• Develop cost-effective, high-temperature materials compatible with thermochemical processes.</li> </ul>	28+ Quarters/ Barriers V, W, X
20	<p><b>Ultra-High-Temperature Hydrogen Production (1000°-3000°C)</b></p> <ul style="list-style-type: none"> <li>• Evaluate ultra-high temperature heat sources.</li> <li>• Evaluate ultra-high-temperature thermochemical water-splitting cycles and direct water splitting.</li> <li>• Evaluate materials and reactor designs for ultra-high-temperature thermochemical processes.</li> </ul>	28+ Quarters/ Barriers V, W, Y

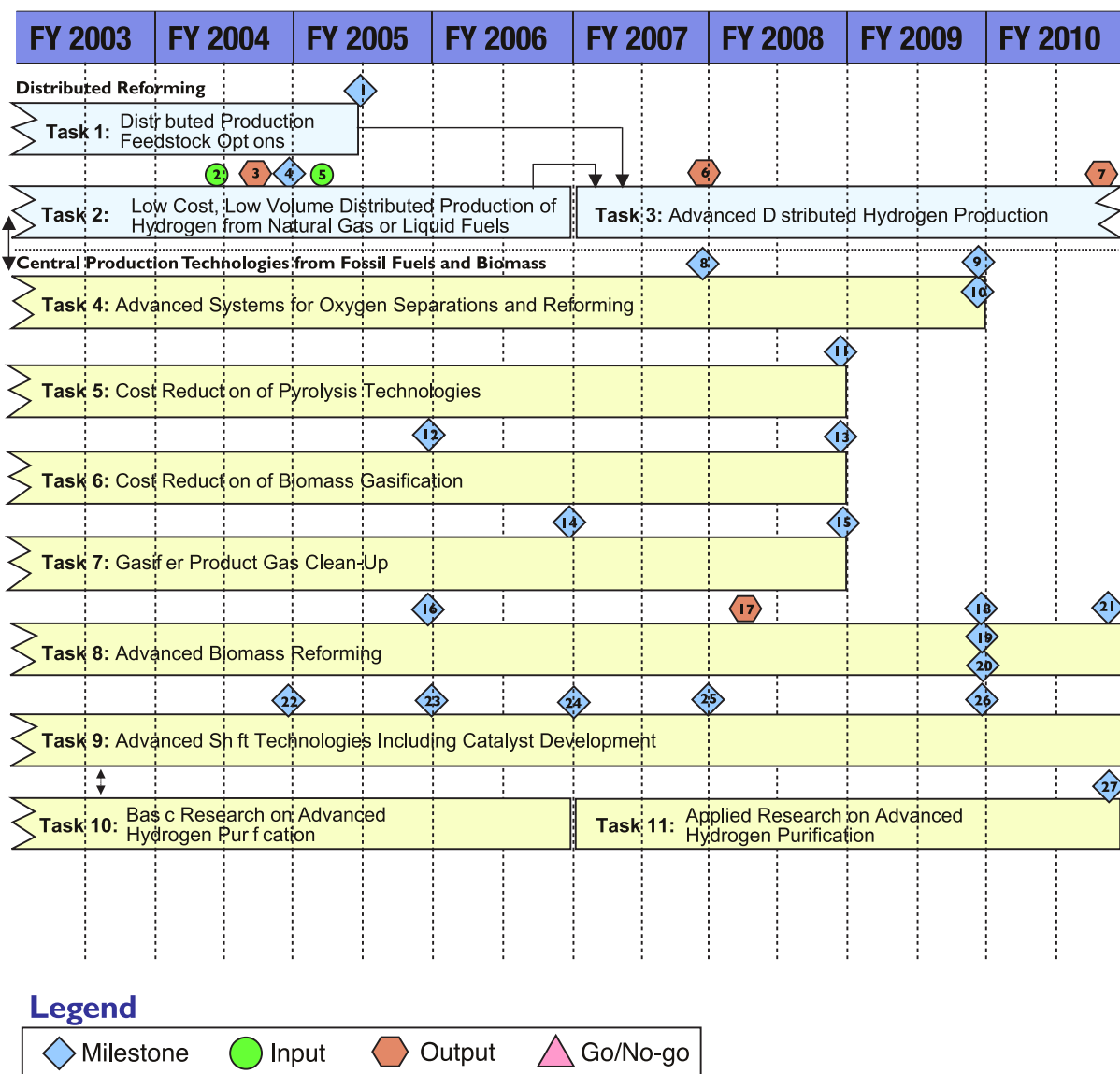
### 3.1.6 Milestones

Figure 3.1.4 shows the interrelationship of milestones, tasks, supporting inputs from other program elements, and technology program outputs for the Hydrogen Production program element from FY 2004 through FY 2010. This information is also summarized in Table B.1 in Appendix B.

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Figure 3.1.4. Hydrogen Production R&D Network



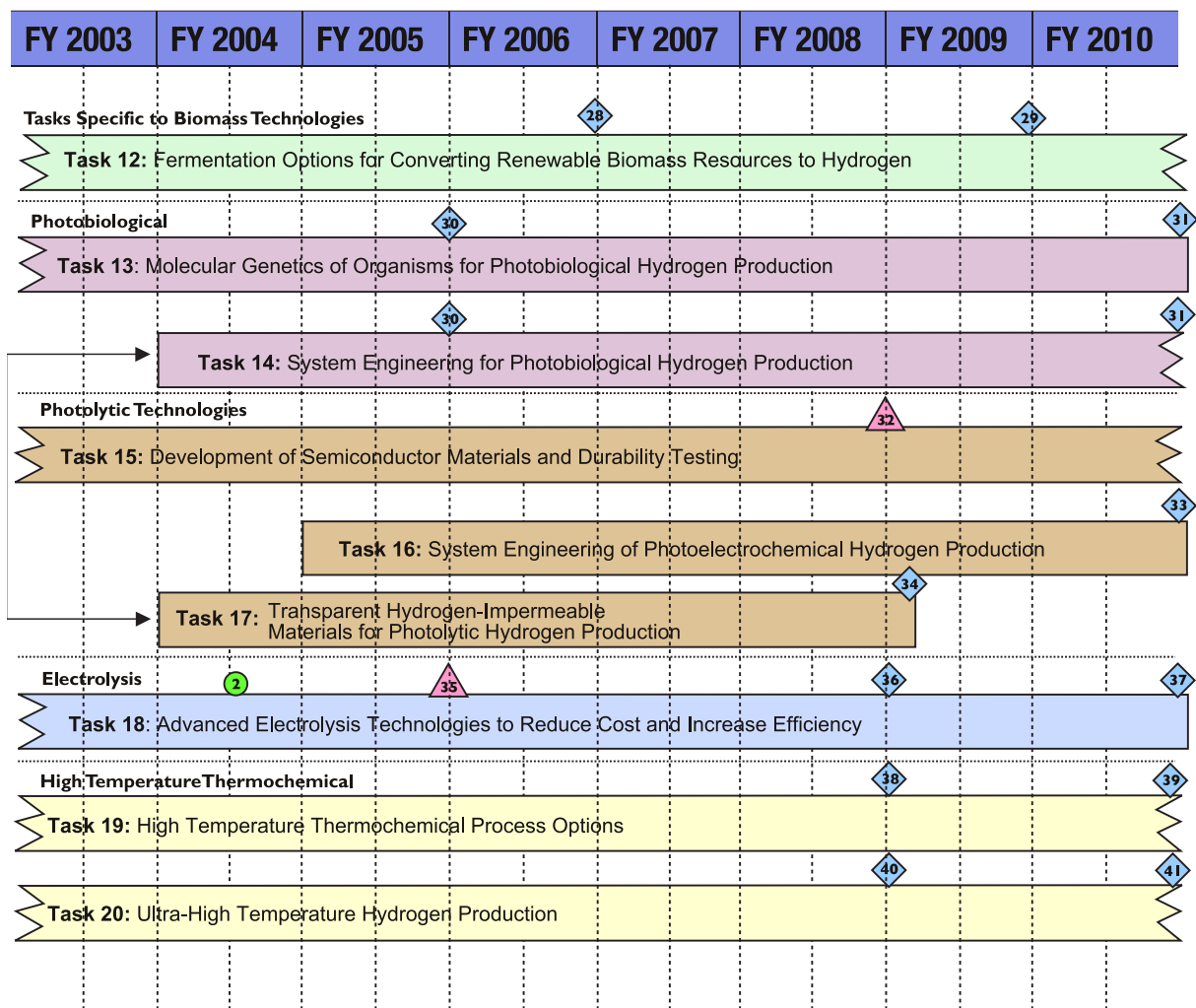
For chart details see next page.

1. Downselect feedstocks for distributed hydrogen production.
  2. Input from Safety: Safety requirements and protocols for refueling
  3. Output to Technology Validation: Hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of \$3.00/kg hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
  4. Complete pilot-scale testing of hydrogen membrane reactor DFMA methods.
  5. Input from Fuel Cells: Fuel-flexible fuel processor technology
  6. Output to Technology Validation: Hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of \$2.50/kg hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
  7. Output to Technology Validation: Hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of \$1.50/kg hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
- 
8. Select membrane system for oxygen/air separations.
  9. Select improved, impurity-tolerant reforming catalysts.
  10. Demonstrate pilot-scale integrated oxygen membrane/gasification reactor.
  11. Verify at pilot scale (100 kg H<sub>2</sub> per day) technologies to reduce the cost of biomass pyrolysis, with operational efficiency improvements to include reduced coking and improved feeding mechanisms.
  12. Select biomass gasification technologies for development based on potential to reduce biomass-to-hydrogen cost.
  13. Complete development and testing of pilot-scale biomass gasification technologies.
  14. Select cost-effective hot gas clean up technology.
  15. Verify cost-effective gasifier product gas clean up.
  16. Select reforming reactor technologies for development.
  17. Output to Technology Validation: Hydrogen production system making hydrogen for \$2.60/kg from biomass at the plant gate
  18. Verify advanced catalysts and reactor configuration for fluid-bed reforming of biomass pyrolysis liquid at pilot scale (500 kg H<sub>2</sub> per day), with catalyst attrition rates less than 0.01% per hour.
  19. Verify technologies for catalyst improvement for reforming of biomass gasifier producer gases at pilot scale (500 kg H<sub>2</sub> per day), with LHV conversion efficiencies of 89%.
  20. Complete development and testing of high-efficiency, advanced biomass reformer reactor technologies.
  21. Verify biomass-based production of hydrogen at projected plant gate cost of \$2.60/kg .
  22. Select pathways for improving conventional water-gas-shift catalysts and reactors, including single stage shift, for further research.
  23. Complete design and testing of bench-scale membrane reactor to carry out shift conversion and hydrogen separation.
  24. Verify cost-effective hydrogen separation membranes with a flux rate of 100 scfh/ft<sup>2</sup> for \$150/ft<sup>2</sup>.
  25. Select advanced shift catalysts that are more efficient and impurity tolerant.\
  26. Verify engineering scale (100-L empty-bed reactor volume) bioreactor that performs the water-gas-shift reaction.
  27. Verify hydrogen purification technology that reduces the cost of hydrogen separation and purification by 30% compared to today's PSA technology.

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Figure 3.1.4. Hydrogen Production R&D Network Continued



### Legend



For chart details see next page.

28. Select fermentation technologies to be developed for converting renewable biomass resources to hydrogen.
  29. Downselect fermentation technologies for converting renewable biomass resources to hydrogen.
30. Develop a photobiological system with the potential for 10% utilization efficiency of absorbed light energy and 0.5% absorbed light to hydrogen energy efficiency that produces hydrogen (at laboratory scale) continuously for 500 hours at a projected cost of \$100/kg.
  31. Demonstrate (at laboratory scale) a photobiological system with 20% utilization efficiency of absorbed light energy and 5% absorbed light to hydrogen energy efficiency that produces hydrogen continuously for 1500 hours at a projected cost of \$30/kg.
32. Go/No-Go: Identify materials/systems that could achieve >10% solar-to-hydrogen efficiency, with projected durability of 10,000 hours, with a cost approaching \$22/kg.
  33. Verify (at laboratory scale) a photoelectrochemical water-splitting system that could produce hydrogen at a projected cost of \$9/kg at the plant gate with technology concepts identified to further reduce these costs.
  34. Select cost-effective transparent hydrogen impermeable material for photolytic production.
35. Go/No-Go: Decision on high-temperature steam electrolysis based on a complete technoeconomic analysis and laboratory-scale research results.
  36. Verify \$2.00/kg plant gate hydrogen production from centralized electrolysis.
  37. Verify renewable integrated hydrogen production with water electrolysis at a hydrogen cost of \$2.50/kg (electrolyzer capital cost of \$300/kWe for 250 kg/day at 5,000 psi with 73% system efficiency).
38. Verify an effective integrated high-temperature chemical-cycle/water-splitting thermochemical hydrogen production at a pilot scale.
  39. Initiate the design of a demonstration-scale nuclear energy enabled high-temperature chemical-cycle/water-splitting production system that projects to a cost of <\$2.00/kg of hydrogen at the plant gate by 2015.
  40. Downselect viable chemical-cycle/water-splitting or other chemical splitting cycles for ultra-high-temperature thermochemical production.
  41. Verify (at small scale) an ultra-high-temperature chemical-cycle/water splitting or other chemical-splitting cycle that projects to a cost of <\$5/kg of hydrogen at the plant gate.